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Development of a Risk Assessment Tool for CO_2 Geological Storage: 'GERAS-CO_2GS'

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Abstract

In this paper we introduce our researches on development of a risk assessment tool for geological CCS (Carbon Dioxide Capture and Storage) that covers geological strata, marine environments, ground surface, ambient air and injection site and its vicinity. To obtain risk values in mentioning area: 1) we have been analyzing CO_2 migrations in relation with various geological properties including flow rate of aquifers, faults, by laboratory experiments and numerical simulations. 2) We also have been analyzing dispersion of CO_2 from ground surface to ambient air using ADMER 2.5 simulation program. 3) Our analysis about marine environments has just started. Diffusion of CO_2 and heavy metals, and their impact on benthos and marine planktons is going to be analyzed by experimental and simulation studies. 4) As regard with risks in ground surface, we are evaluating CO_2 related safety risk levels of injection facilities by analogical industrial accident statistics including high-pressure gas laboratories. We are developing risk assessment tool, named GERAS-CO2GS (Geo-environmental Risk Assessment System, CO_2 Geological Storage Risk Assessment System), to analyze risks in relation with migration of injected CO_2, and to assist safety and risk management. At this moment, GERAS-CO2GS calculates CO_2 retention and leakage of geological strata models. We are going to add some risk scenarios including near ground surface and sea, so that the system will evaluate total risks of geological CCS. We are going to combine results of above-mentioned researches into GERAS-CO2GS program accordingly. On the other hand, risk data will be stored in GERAS-CO2GS categorized by endpoints. It is expected that development of GERAS-CO2GS will contribute to risk assessment of the individual injection sites. It will facilitate understanding of risks around geological CCS by legislators and peoples around injection site.

Keywords: Geological CO_2 sequenstration, CCS, risk assessment, software development, accident statistics, desaster rate, high-pressure gas

1. Introduction

For gaining public recognition about feasibility of Geological CCS (Carbon dioxide Capture and Storage) in adjacent area of injection planned site, it is important to quantitatively estimate risks and to prove the level of the risk being negligible. Generally, as a matter of course risk assessment procedure, potential hazards should be identified every

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elements of Geological CCS such as: reservoirs or aquifers, cap rock, upper layers, CO_2 injection well, CO_2 supplying installations and CO_2 transport facilities. Among various expected hazards, $C0_2$ leakage is crucial. It is because the rate of CO_2 retention presents the efficiency of the primary purpose of geological CCS (i.e. reduction of CO_2 gas emission to ambient air), and it is clue to understand risk of a specific injection plan.

In this paper, we introduce our researches to evaluate risks around Geological CCS including CO_2 migration, leakage, dispersion to ambient, and analysis of safety risks, and to develop a risk assessment tool.

2. Objective of the research

2.1. Needs of risk assessment

There are three major needs to establish risk assessment methodology of geological CCS:

The first one comes from individual geological CCS sites. Each CO_2 injection site has to manage risks for their proper operation through lifetime of geological CCS: site selection, well opening, injection, closing well and stewardship of the site [1]. Risk assessment of individual CO_2 injection site is essential process to manage site operations. It is also important to estimate the efficiency of greenhouse gas reduction in specific injection projects.

Second need comes from an aspect of public acceptance building. In individual geological CCS site, result of risk assessment is essential as it offers logical evidences to risk communicators.

When install and progress a new technological project in a specific site, it is essential to establish public acceptances. When local residents or local government throw questions against the safety and size of risk of the CO_2 injection project plan, project managers should explain the size of risks in easy understandable manner. Preliminary risk assessment in planning stage of a project will offer the fundamental evidences for concerned peoples [2, 3].

There are some reports of successful public acceptance building from Australia, Germany and USA [3, 4, 5, 6]. On the other hand, some reports describe about failures of public acceptance building and analyze the reason why their activities resulted discontinuity of the projects [7, 8, 9].

The third demand comes from risk governance needs by legislators, administrators, economy and society. They need criteria to design legislation for new emerging technology, to approve geological CCS projects proposal in their vicinities, and/or to insure or subsidize geological CCS projects.

In COP17 (November 2011), inclusion of geological CCS into CDM (Clean Development Mechanism) scheme was decided [10]. It was also decided that risk assessment, including quantitative estimation of CO_2 leakage, would be done in the course of proposals of Geological CCS projects. Therefore, project managers, who want to operate a geological CCS under CDM scheme in subjected countries, have to prepare quantitative estimation of efficiencies of greenhouse gas reduction of the project, and results of quantitative risk assessment it proves impacts on surrounding area will be negligible.

On the other hand, ISO/TC 265 CCS was settled in 2012 spring, and discussions for international standardization of geological CSS has been started. Abreast with movements of international organizations, IEA/GHG membership countries are preparing or enacting domestic rows and/or local standards for large-scale experimental geological CCS projects [11, 12, 13, 14].

It is pressing issue to establishment risk assessment methodologies which capable for individual geological CCS site.

2.2. Objective of the research and area of consideration

To meet above-mentioned three emerging demands, we have been researching risk assessment methodologies and have been developing a risk assessment tool.

Our consideration involve: underground strata, marine environments, ground surface and ambient air (Figure 1). Our research includes risk analysis of CO_2 migration, dispersion CO_2 and other geological CCS related substances in concerned areas. There are some types of Geological CCS when categorize by strata of injection targets: shallower aquifers, deep brine aquifers, deep oil and/or gas reservoirs. Targets of our research are shallower aquifers and depleted deep oil and/or gas reservoirs.

In risk assessment of geological CCS, essential issues are evaluation of CO2 retention and leakage rates and volumes. Once CO_2 retention and leak rate for various risk scenarios are evaluated, we will be able to evaluate greenhouse gas reduction effect, environmental impacts, and/or safety impacts around injection site and adjacent areas.

As geological CCS is relative new technology, there are insufficient accumulations of data to evaluate frequencies and consequences of risks quantitatively [15]. When assess general risk level of a newly developed industrial technology, PHA (Preliminary Hazard Assessment) is one of useful methodologies to identify and quantify inherent risks roughly. In the case of geological CCS operation, PHA will consider following subsystems: target reservoir or aquifer, cap rock, upper layer, CO_2 injection well, CO_2 injection plant and CO_2 transport facilities. For each subsystem, PHA will estimate hazards (likely failure or accident), its frequencies (likelihood) and risk (consequences, impact). Conducting PHA we will 1) decide hazard frequency and consequences using statistics of similar technologies, 2) calculate risks of specific phenomena by numerical simulations, and 3) evaluate safety and environmental impacts around injection site [16].

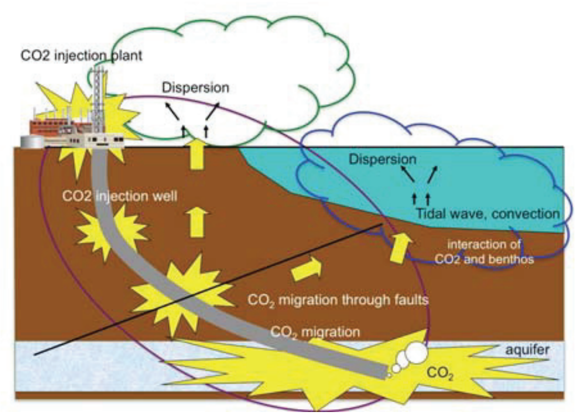


Figure 1 Area of consideration

3. Development of a risk assessment tool

As described above, primary issue to be assessed is CO_2 retention rate within strata and injection facilities. Once CO_2 retention and leak rates are estimated, we will be able to evaluate efficiencies of greenhouse gas reduction. And furthermore, we will be able to estimate environmental and safety impacts on injection site and its vicinity.

We are considering the following hazard scenarios: CO_2 migration from deep underground strata to shallower area and seepage to ground surface, CO_2 leakage from well or ground surface facilities by accidents.

Aiming to estimate CO_2 migration and to evaluate risks in around geological CCS site, we are developing GERAS-CO2GS[†] [17, 18]. It is expected that GERAS-CO2GS would assist peoples understanding of risks around individual Geological CCS site.

Major function of GERAS-CO2GS is estimation of CO_2 retention and migration volumes, so far. As regard with CO_2 retention and leak rate used in GERAS-CO2GS, we are gathering data from laboratory experiments and numerical simulations. In the course of PHA analysis, we also gather accident data of ground surface. Collected risk data has been integrated into GERAS-CO2GS one by one.

3.1. Outline of GERAS-CO2GS

Goals of GERAS-CO2GS development are: to evaluate volumes and rates of CO_2 leakage, impacts on vicinity of injection site, ground surface, marine environment and ambient air.

GERAS-CO2GS is presently at prototype stage. It calculates CO_2 retainment and leakage volume for each segment of geological model, and it displays calculated values on the screen (Figure 2). GERAS-CO2GS also process CO_2 dispersion on the ground surface and output kml files so that Google earth can display. GERAS-CO2GS has four routines to actualize those functions (Figure 3).

For numerical estimation of surface dispersion of CO_2, we are using ADMER 2.5 (Atmospheric Dispersion Model for Exposure and Risk Assessment, AIST), which calculates ambient dispersion of gases depend of weather conditions [19].

[†] GERAS CO2GS: Geo-environmental Risk Assessment System for CO2 Geological Storage

GERAS-CO2GS contains four major routines. Figure 3 shows the flow chart:

a. Calculate CO_2 retention and leakage
b. Define and edit of risk data
c. Process CO_2 dispersion on the surface
d. Evaluate risk

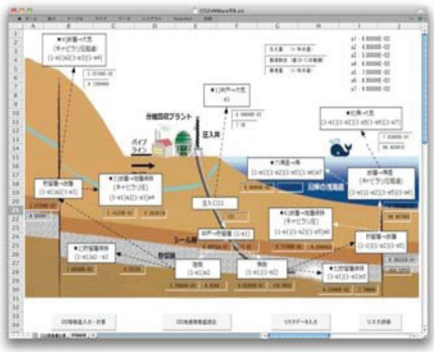


Figure 2 Screen shot of GERAS-CO2GS's output window. (Captions are Japanese.)

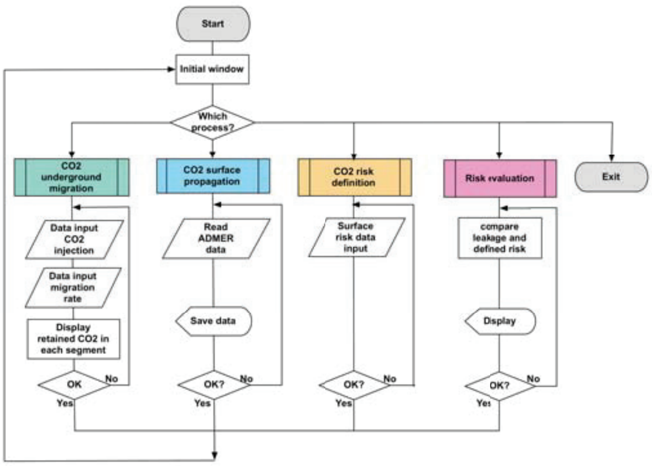


Figure 3 Process flow of GERAS-CO2GS

3.2. Calculation of CO_2 retainment and leakage

GERAS-CO2GS has geological models of CO_2 injection site, those consisted from following segments: injection well, reservoir, cap rock, upper seam, fault, seabed, and sea, sea-surface. Being given CO_2 injection rate and CO_2 retaining rate of each segment, GERAS-CO2GS will calculate volume of retention.

When CO_2 retaining rate of each segment $i = (1,\ldots,n)$ is presented by equation (1), retaining rate of whole CO_2 injection site model will be presented by equation (2).

$$\mathrm{CO_2 retained\ rate}_i = 1 - \mathrm{CO_2 leaked\ rate}_i \qquad (1)$$

$$\mathrm{Total\ CO_2 retained\ rate}_i = \prod_{i=1}^{n}(1 - \mathrm{CO_2 leaked\ rate}_i) \qquad (2)$$

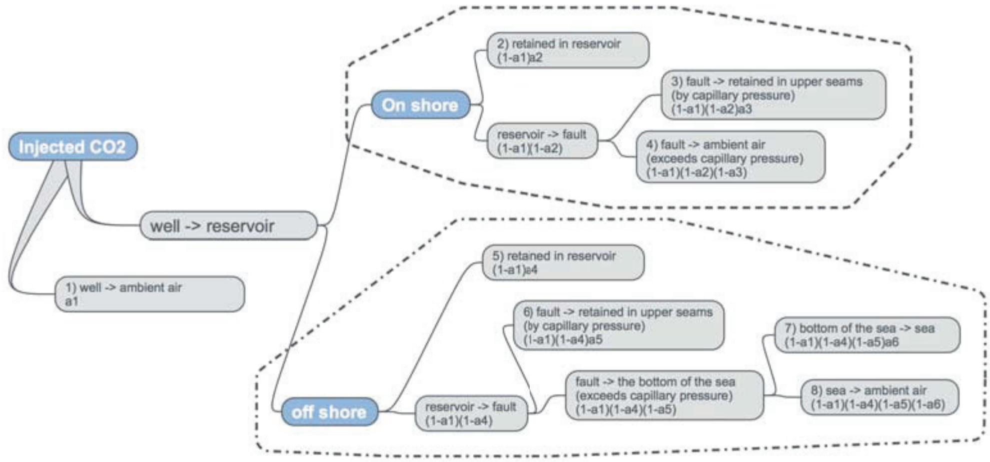


Figure 4 Logic of calculation of CO_2 retain rate and leak rate.

GERAS-CO2GS calculates CO_2 retention and leakage in accordance with equation (1) and (2), for a segment by a segment. Figure 4 shows concept of calculation of each segment. Data from laboratory experiments and numeric simulations are applied as CO_2 retain rate for each segment [20, 21].

3.3. Risk data

GERAS-CO2GS stores risk data of various endpoints. At this moment, impacts of ambient CO_2 concentration against human and plants are able to use risk calculation. Other than ambient concentration impact data, GERAS-CO2GS stores data of soils, human residence and potable water.

4. Researches to extend GERAS-CO2GS

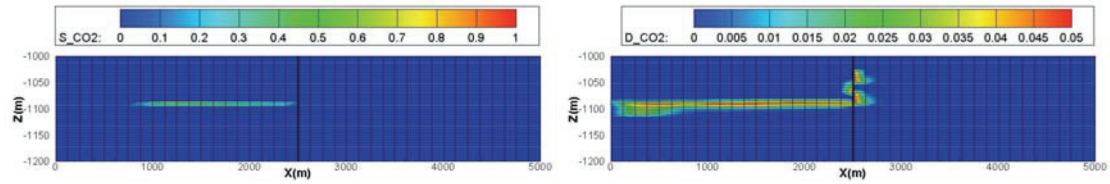
As described in previous chapter, our consideration covers underground, sea, ground surface, ambient air, and vicinity of injection site. In this chapter, we describe our researches on these areas.

4.1. Migration of CO_2 in geological strata

The leakage of injected CO_2 due to the existence of geological faults is expected to be one of the principal hazards in geological CCS to aquifers. Therefore, it is important to predict the migration of injected CO_2 in relation with time and space under given underground conditions: such as permeability, porosity and the existence of fault. For risk assessment, it is necessary to quantitatively estimate the amount of storage and leakage of injected CO_2. Concerning to numerical simulation of CO_2 migration in underground via fractures and faults, we constructed the reservoir model that aquifer and impermeable layers were alternately located in vertical direction of reservoir. Modeling of the fault was simplified by putting the thin zone that simulated the fault inside of analytical mesh zone. Using the constructed reservoir model, we carried out some simulation run by CO2/PENS (developed by LANL, utilized under MOU agreement) [20].

We considered the effect of each parameter on flow behavior of CO_2 in an aquifer and quantified the amount of CO_2 leakage, while changing calculation parameters: geological structures, faults, absolute permeability of fault and flow velocity of groundwater. Through these numerical studies, we predicted the degree of worst scenario of injected CO_2 leakage. For improving the accuracy of prediction, it is important to prepare the basic parameter of a real storage site in Japan such as scale, thickness of layer, porosity, permeability, etc.

As the result of numerical simulation study, it revealed: To predict migration of injected $C0_2$ dependent on time and space porous media (rocks), the essential parameter is permeability against supercritical $C0_2$ and water are. Therefore we carried out experimental study. Using sand column, we examined flow behavior of supercritical $C0_2$ and water in porous media. Grain size and temperature were changed as an experimental parameter [21].



Liquid CO_2 (Model3) Dissolved CO_2 (Model3)

Figure 5 The distributions of liquid CO_2 (supercritical CO_2) and dissolved CO_2 in x-z plane of aquifer after 250years. In this numerical simulation, 10,000 ton/year CO_2 is injected into an aquifer model of alternate layer of sandstone and mudstone. Mass flow rate is applied to each node from -1090 to -1100m at x=125m and y=2500m as injection point (injection well) [20].

We analyzed laboratory-scale experiment data with numerical simulation to clarify permeability characteristics of supercritical $C0_2$ in porous media. As relative permeability model for simulation, we used the extended Corey model that indices Nkrg and Nkrw were introduced. By changing the values of Nkrg and Nkrw, we conducted history matching of flow behavior and pressure change during both of $C0_2$ and water injection processes. Then we could obtain optimized relative permeability curves that allow us to reproduce $C0_2$-water multi-phase flow. (Figure 6 shows an example of analytical result. It is optimized relative permeability curves depending on temperature of the experimental cell.)

Comparing the optimized relative permeability curves in the process of $C0_2$ injection, it revealed that: 1) water mobility was relatively high compared with that of $C0_2$ when grain size was large and 2) relative permeability to $C0_2$ became higher under the condition below critical point of $C0_2$.

We interpreted transport phenomena of $C0_2$ after shutoff of $C0_2$ injection on the basis of relative permeability curves obtained for water injection process. As a result, it was found that 1) liquid $C0_2$ easily migrated into geological formation in the cases of small grain size and low temperature and 2) dissolved $C0_2$ migration due to groundwater flow contributed to the change of $C0_2$ distribution under the condition of high water saturation.

In addition, recently, we are extending our analysis and are examining leaks around the injection well and its impacts.

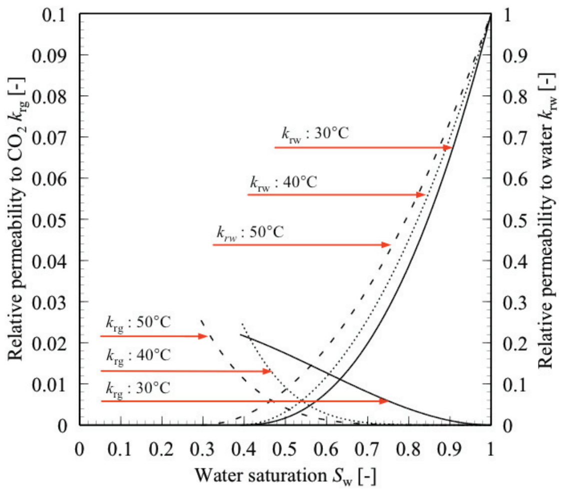


Figure 6 Optimized relative permeability curves for CO_2 injection process through series of numerical analysis. It shows temperature dependencies of relative permeability curves. [21]

4.2. Diffusion of CO_2 into the atmosphere

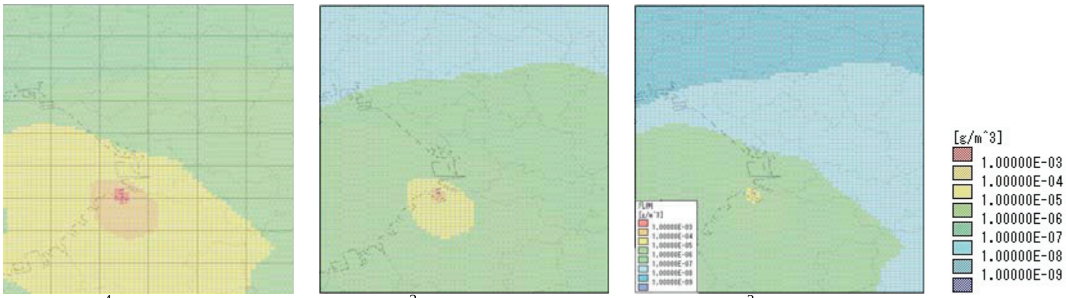
In IPCC SR, there is a description about retention and release rate of geological CCS [22]. As for CO_2 retention rate, they expect 99% for 100 years, and over 99 % for 1000 years. These estimations include both underground and ground surface facilities. Conversely it would be say that, it was expected less than 1 % leakage for 100 years from whole geological CCS facilities.

To understand effect of various level of CO_2 diffusion on the ground surface and its impact, we carried out numerical simulation using an atmospheric dispersion model, AIST-ADMER ver.2.5 [19]. We assumed a 10^5 ton/year of CO_2 injection rate as a model case, as it is the average injection rate of EOR in oil field [23]. In calculation, we applied Tokyo bay geometric model. It is relatively flat landscape. We set a leak area in seashore where wind is stronger than inland. We apply various weather conditions from National Meteorological Observatory data. For calculation of diffusion, we set 100m×100m grid size. Considering the IPCC SR's expectation, we set three of leakage rate near to 1%:

a. 0.1%, 10^2 ton/year
b. 1%, 10^3 ton/year
c. 10%, 10^4 ton/year

Figure 7 shows the result of simulation [24]. Length of a side is about 37 Km. In Figure 7 a., red area indicates high CO_2 concentration (10^{-3} g/m^3) area. In a few kilometers distance, it is diffused and diluted by wind, and the concentration decreases by 10^{-4} g/m^3. It is far smaller than concentration of natural ambient air (6×10^{-1} [g/m^3]), and the level of CO_2 is none-toxic for animals and plants.
As described above, map grid size for calculation is 100m square. From this simulation, it is not predictable the highest concentration in the center grid of seepage. Therefore, it could say from this numeric simulation: if CO_2 exude from some extent area of ground surface in steady speed, the risk in outer area of a few 100m radius will be negligible even it will leak in 10^4 ton/year rate.

Other than Figure 7 case (Tokyo bay as geometric model), we also applied the same simulation in a volcano crater geometric model. In that case, CO_2 stays inside of the crater and it seemed difficult to be dilute by wind. In Japan, they consider plain seashore site or offshore site for geological CCS projects. It shall have advantages to diffuse and to dilute CO_2 gas when it once leaked.



a. 10%, 10^4 ton/year b. 1%, 10^3 ton/year c. 0.1 %, 10^2 ton/year

Figure 7 Results of numerical simulation of CO_2 diffusion from ground surface into ambient. For calculation with ADMER 2.5, weather condition of average January day data, and Tokyo bay geometric model is used. Length of a side is abut 37 Km. [24]

4.3. CO_2 migration into sea

As described above, our consideration involves marine environment (Figure 1). We've just started the research. The research includes diffusion of CO_2 and heavy metals, and their impact on benthos and marine planktons. The result of it will be reported in near future.

4.4. Risks in ground surface around injection site

We would like mention about safety risks on the ground surface around CO_2 injection site.
On the ground surface area, we have to consider two types of risks: risks those defined by industrial safety, and risks of environmental context. In this section, we pick up industrial safety side risk.

4.4.1. Sources of CO_2 related Accidents and Disaster Cases

As regard with Geological CCS, there is not sufficient history of operations for to derive risk values on the ground surface: i.e. disaster rate. In such conditions, the simplest way to estimate safety risks is to refer industrial disaster records and statistics. Researching disaster or accident records in similar industrial fields, we will be able to estimate risk levels of the area.

To estimate risk level on ground surface, we have researched Japanese industrial disasters those related with CO_2 gas. There are some databases those store industrial disaster record in Japan (Table 1). Among them, the 'High-Pressure Gas Accident Database (HPGA-database)' stores largest number of accidents (9974 cases).

HPGA-database stores accident cases those are covered by high-pressure gas safety act and its regulations in Japan. The high-pressure gas safety act regulates 'the production, storage, sale, transportation and other matters related to the handling of high pressure gases, their consumption as well as the manufacture and handling of their containers'. The act aims 'to secure public safety by preventing accidents and disasters caused by high pressure gases' [25]. Accordint to the demand of high-pressure gas safety legislations, HPGA-database stores accident cases that relate with the act including cases of high-pressure gas producing laboratories, retailers, consumers, and transportations.

CO_2 gas is easy resolvable to water and forms carbonic acid which is unstable and easily be isolated. But, CO_2 gas is not combustible itself. Therefore, it is hard to imagine unexpected sudden accidents would happen. Nevertheless, many CO_2 compressed gas related accidents have happened in industries.

In the following subsections, we analyze the CO_2 gas related accidents based on analysis of HPGA-database.

Table 1 Referable Disaster Databases those store CO_2 related accidents and disasters cases in Japan

Name of Database	Organization	Duration	Kind of stored data
High Pressure Gas Accident Database (HPGA-Database) [26]	High Pressure Gas Safety Institute of Japan	1966-2011	High Pressure Gas accidents
Accident and Disaster Database [27]	Non-Life Insurance Rating Organization of Japan	1997-2007	General accidents and disasters
RISCAD [28]	National Institute of Advanced Industrial Science and Technology	1949-2010	Chemical disasters
Occupational Accident Database [29]	Ministry of Health, Labor and Welfare	N/A	Occupational accidents

4.4.2. CO_2 related accident cases in high-pressure gas producing laboratories

To examine some sort of analogy with geological storage, we focused on 'high-pressure gas production industries' in HPGA-database. Number of CO_2 related accident cases in 'high-pressure gas production laboratories' for whole time range (1966-2011) and recent five years (2006-2010) are, 65 and 25, respectively (Table 2 and Table 3).

When calculate average yearly accident rates, it is 5/year and 1.4/year for 2006-2010 and 1966-2011, respectively. Recent yearly accident rate is rather worse than total duration average. This would be conveyed by mixed economical reasons like; matured industrialized society requires sufficient maintenance efforts; recent economical recession would prevent to replace installations in proper intervals, etc.

Among 25 cases that happened between 2006 and 2010, 24 cases were 'leakage', and the rest was a case of 'theft'.

4.4.2.1. CO_2 leakage accidents in high-pressure gas production laboratories

Table 2 Causes and number of casualties of accidents in high-pressure gas production laboratories (1966-2011)

Type of accident	**Number of cases (Ratio %)**	**Fatalities**	**Seriously injured**	**Slightly Injured**
Leakage	57 (87.7%)	2	1	11
Theft or lost	3 (4.6%)	0	0	0
Rapture of pressure vessels	5 (7.7%)	4	1	38
Total	65(100%)	6	2	49

Table 3 Causes and number of casualties of accidents in high-pressure gas production laboratories (2006-2010)

Type of accident	**Number of cases (Ratio %)**	**Fatalities**	**Seriously injured**	**Slightly Injured**
Leakage	24 (96.0%)	0	0	1
Theft or lost	1 (4.0%)	0	0	0
Total	25 (100%)	0	0	1

Table 4 Causes of leakage accidents in high-pressure gas production laboratories

Cause of leakage	**1966 - 2011 Number of cases (%)**	**2006 - 2010 Number of cases (%)**
Corrosion, metal fatigue	27 (47.4%)	19 (79.1%)
Human error	29 (50.9%)	4 (16.7%)
Earthquake	1 (1.8%)	1 (4.2%)
Total	57 (100%)	24 (100%)

Table 4 shows causes of leak accidents in high-pressure gas production laboratories. Major causes of 24 leakage cases were 'corrosion or metal fatigue' (79.1 %): i.e. corrosion in pipes, coils and evaporators, and metal fatigue in vent pipes induced by vibrations of compressors. Next cause was 'human errors' (4 %) in opening or closing valves. As regard with 'earthquake' case (4.2 %), it happened in 2009. When the earthquake happened, a 7kg CO_2 cylinder came down. The shock Loosen a valve and CO_2 was leaked.

4.4.2.2. Rapture of CO_2 pressure vessels in high-pressure gas production laboratories

In Table 3, the ratio of 'rapture of pressure vessel' of recent 5 years is 0 %. It is drastic difference from 7.7 % in total duration in Table 2. Perhaps, it would be outcome of improvements of manufacturing technology of high-pressure vessels and safety management.

In high-pressure gas production laboratories, five rupture cases had happened (Table 5). It caused two cases in 1960's, and each of rests happened in1989, 1998 and 2011 respectively. Among five cases, two cases were caused by human errors in opening or closing valves during maintenance; the other two cases were corrosion of pipes or deterioration of vessel wall by aging; and arson in which a bone fire had made under the high-pressure vessel of CO_2.

Table 5 Cause of rapture of pressure vessel accidents in high-pressure gas production laboratories in Japan, 1966 - 2011

Cause of rapture of pressure vessels	Number of cases
Human error	2 (40%)
Corrosion or deterioration by age	2 (40%)
Arson	1 (20%)
Total	5 (100%)

4.4.3. CO_2 related accident cases in wells

They have been experiencing CO_2 related accidents in oil or gas wells some times:

In 1998, a CO_2 blowout accident had happened in CO_2 injection well for EOR, in Nagylengyel, Hungary [30, 31]. At first they mistakenly dropped a packer to the bottom of a well (-2175m level). They removed a blowout preventer to retrieve the packer, and suddenly CO_2 gas had blew out. The gas contains about 10% of H_2S. Concentration of H_2S in the ambient air was increased up to 20ppm at the maximum. Municipal government made 5000 local residents to evacuate. The blowout had continued for 60 hours until they succeeded to seal the well.

The accident changed soil property, gave impact on plants and made residents evacuate. On the other hand, none of serious impacts on water quality was observed in near lakes.

Other than Hungary's case, there is an analytical report of accident statistics of injection wells for EOR in southern California, USA [32]. They analyzed about 230 thousands records of well operations, which had performed between

1991 and 2005. Well operations involve: well drilling, reworking, servicing, abandoning and others.
Blowout had occurred 1 ~ 10 cases / year. The frequencies of blowouts were 0.029 ~ 0.059 %/operation, depend on well operations. About 10% cases had incurred casualties. They had recovered about 3.5 days in average.

These accident cases were happened in EOR wells. As described above, targets of our research involves shallower aquifers and depleted deep oil and/or gas reservoirs. As for shallower aquifers, we have to survey and find other accident data to presume accident rates in near future.

5. Discussion

In previous chapters, we introduced our researches: development of a risk assessment tool for geological CCS and related researches those covers geological strata, sea, ground surface, ambient air and injection site and its vicinity.

5.1. Analysis of risks of CO_2 migration and dispersion

As regard with underground strata, we have been analyzing CO_2 migrations in relation with various geological properties including flow rate of aquifers, faults, by laboratory experiments and numerical simulations using CO2-PENS. Addition to the researches, recently, we are examining leaks around the injection well and its impacts.
Concerning to the ambient air, we have been analyzing dispersion of CO_2 from ground surface to ambient using ADMER 2.5. We are going to extend our concerns of analysis more sites specific and include other substances too.
ADMER 2.5 is applicable for environmental issue analysis. When we consider sudden accidental flows like rupture of vessels or blowout of well, we have to use some tools for industrial safety analysis.
Our research about inclusion of marine environment into GERAS-CO2GS has just started. Diffusion of CO_2 and heavy metals, and their impact on benthos and marine planktons is going to be analyzed by experimental and simulation studies. The result of this topic will be reported in near future.

5.2. Risks in ground surface facilities

In this subsection, we would like discuss about CO_2 related risks in ground surface facilities.
In previous chapter, we examined statistics of high-pressure gas accidents those caused in Japan. In Japan, average CO_2 production was about 900,000 ton/year, between 2006 and 2010 [33]. When divide number of accidents in high-pressure gas production laboratories between 2006 and 2011 (Table 3) with CO_2 production rate, it produces accident rate of CO_2 production laboratories of referred years.

Table 6 Accident and casualties rate of CO_2 gas producing laboratories (average data between 2006 and 2010)

Item	**Rates**
Accident rate	0.6 / 10^5 ton CO_2 Production • year
Leak accident rate	0.5 / 10^5 ton CO_2 Production • year
Fatality rate	0 person / 10^5 ton CO_2 Production • year
Serious injury case rate	0 person / 10^5 ton CO_2 Production • year
Slight injury case rate	0.02 person / 10^5 ton CO_2 Production • year

When presume CO_2 related accident rate of ground surface facilities, we think it would be suitable to use accident cases of CO_2 produce factories (Table 3), because of similarity in handling volumes of CO_2 gas. Table 6 shows rate of accident and casualties in CO_2 production laboratories.
Geological CCS is different from CO_2 gas production obviously, but total quantities of handling CO_2 gas in activities are similar. CO_2 retailers and consumers handle far small volumes of CO_2 compare to geological CCS. Therefore, we propose: accident and casualties rates of ground surface facilities of CO_2 injection will have analogy with order of Table 6 values.

In further work, we are going to search and analyze accident cases those had happened around wells, and are going to consider risk values of them. As our research targets are shallower aquifers and depleted deep oil and/or gas reservoirs, we have to survey both types of accident cases.

5.3. Further Modifications of GERAS-CO2GS

Development of GERAS-CO2GS is presently at the prototype stage. It calculates CO_2 retaining and leaking volume for each segment of Geological model. It displays the calculated values on screen (Figure 2) and evaluates risks against human and plants. GERAS-CO2GS also process CO_2 dispersion on the ground surface and output 'kml' files so that Google earth can display.

Our final goal is to make GERAS-CO2GS evaluate volumes and rates of CO_2 leakage and impacts of injection site model: target strata, injection well, reservoir, fault, upper layer, seabed, sea and atmosphere. We also aim to evaluate CO_2 dispersion in marine environments and ambient air on ground surface within it. Therefore, we are going to evaluate environmental impacts and safety impacts on local area, step by step. We are going to combine results of above-mentioned researches into the GERAS-CO2GS program accordingly. On the other hand, risk data will be stored in GERAS-CO2GS categorized by endpoints. Then finalize our total risk assessment tool.
In the future modifications of GERAS-CO2GS, we are going to prepare various risk scenarios including near ground surface and sea, so that the system will evaluate total risk of geological CCS. On the other hand, we also have to develop more precise evaluation logics for vicinity of injection sites.

Developing and publicize the program, we are going to contribute to risk assessment of the individual injection sites. And furthermore, we hope to contribute to legislation bodies and local societies so that they would reduce CO_2 emissions and consume energy rationally.

6. Conclusion

In this paper we introduced our researches about developing a risk assessment tool for geological CCS. Our considerations involve risks of geological strata, marine environment, ground surface, ambient air and vicinity of injection sites.

As regard with underground strata, we have analyzed CO_2 migrations in relation with various geological properties including flow rate of aquifers, faults, by laboratory experiments and numerical simulations using CO2-PENS. Addition to the researches, recently, we are examining leaks around the injection well and its impacts.
Concerning to the ambient air, we have analyzed dispersion of CO_2 from ground surface to ambient air using AIST ADMER 2.5. We are going to extend our researches more site specific and going to involve other substances relate with geological CCS. When we consider sudden accidental flows like rupture of vessels or blowout of well, we have to use some tools for industrial safety analysis.
Our research about inclusion of marine environment into risk analysis has just started. Diffusion of CO_2 and heavy metals, and their impact on benthos and marine planktons is going to be analyzed by experimental and simulation studies.
We presumed CO_2 related safety risk level of injection facilities by analysis of accident statistics of high-pressure gas industry. We also surveyed accident statistics of blowout in EOR wells. For precise risk evaluation, we have to collect and analyze more accident cases and statistics.

We are developing risk assessment tool, named GERAS-CO2GS, for geological CCS risk assessment. At this moment, it calculates CO_2 retention and leakages of geological models.
To extend GERAS-CO2GS and able to assess total risks, we are going to prepare various risk scenarios including near ground surface and sea. On the other hand, we also have to develop more precise evaluation logics for vicinity of injection sites. We are going to combine results of above-mentioned researches into GERAS-CO2GS program accordingly. On the other hand, risk data will be stored in GERAS-CO2GS categorized by endpoints. It is expected that Development of GERAS-CO2GS will contribute to risk assessment of the individual injection sites, and facilitate risk understanding of legislators and peoples around injection site.

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